DEVELOPMENT OF A HIGH TEMPERATURE, HIGH SENSITIVITY FISSION COUNTER FOR LIQUID METAL REACTOR IN-VESSEL FLUX MONITORING*

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ABSTRACT

Advanced liquid metal reactor concepts such as the Sodium Advanced Fast Reactor (SAFR) and the Power Reactor Inherently Safe Module (PRISM) have relatively large pressure vessels that necessitate in-vessel placement of the neutron detectors to achieve adequate count rates during source range operations. It is estimated that detector sensitivities of 5 to 10 $counts \cdot s^{-1} \cdot [neutron/(cm^2 \cdot s)]^{-1}$ will be required for the initial core loading. The Instrumentation and Controls Division of Oak Ridge National Laboratory has designed and fabricated a fission counter to meet this requirement which is also capable of operating in uncooled instrument thimbles at primary coolant temperatures of 500 to 600°C. Components are fabricated from Inconel-600, and high temperature alumina insulators are employed. The transmission line electrode configuration is utilized to minimize capacitive loading effects.

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BACKGROUND

The relatively large pressure vessels of American liquid metal reactor (LMR) concepts such as the Sodium Advanced Fast Reactor (SAFR) and the Power Reactor Inherently Safe Module (PRISM) require that neutron detectors be placed in-vessel to provide adequate neutron sensitivity for source-range operation. Preliminary reactor physics calculations for these reactors indicate that the equivalent thermal neutron flux (nv_{th}) at the detector position will vary from ~0.40 neutrons/($cm^2 \cdot s$) or nv_{th} at shutdown to ~4.5 × 10^9 nv_{th} at full power.[1] Thus, to provide adequate shutdown count rates, a detector must have an equivalent thermal neutron sensitivity substantially in excess of 1 $count \cdot s^{-1} \cdot (nv_{th})^{-1}$ or cps/nv_{th}. An additional requirement for sustained operation at primary coolant temperature (500 to 600°C) leads to the need for a high temperature, high sensitivity fission counter (HTHSFC).

High temperature fission counter development programs have been pursued in several countries including the United States, France, England, and Japan. Irradiations and postirradiation examinations of fission counters developed and tested during these programs have provided valuable data concerning the selection of structural materials, fill gas compositions, fabrication techniques, and assembly procedures.[2-6] They indicate that there is no inherent obstacle to the production of fission counters that can meet LMR temperature requirements. However, without exception, all high temperature counters tested to date have been relatively low sensitivity models with thermal neutron detection sensitivities ranging from 0.1 to 0.7 cps/nv_{th}.

When the previous high temperature test counters were fabricated, fission counters with sensitivities in excess of 1 cps/nv_{th} were difficult to fabricate for several reasons. First, the higher capacitance associated with larger electrode areas led to poor frequency response and low current pulse amplitudes. Second, since uranium is an alpha-emitter, incorporating large quantities of uranium in 'de a counter increases the inherent alpha source to a point at which neutron detection becomes difficult.

Through the use of ultrapure, electromagnetically separated ^{235}U (99.9% ^{235}U; the main alpha-emitting isotope is ^{234}U), ORNL developed a counter in the late 1970s with a sensitivity of ~8 cps/nv_{th}.[7] This counter, designated HSC-1, was essentially an optimization of conventional design techniques,[8,9] and after laboratory testing, we concluded it was near the practical limit of sensitivity for conventional fission counters. Since this design relies on the use of very high purity nuclear materials that were and continue to be in very short supply, it is not economical for a commercial flux monitoring application for which many units will be required.

In 1978, ORNL developed the transmission line fission counter (TLFC)[7,10,11] and subsequently produced prototypes with thermal neutron sensitivities >25 cps/nv_{th} while drawing from relatively abundant inventories of 97% enriched material obtained from diffusion cascades. The TLFC concept decouples otherwise interrelated design parameters and allows the designer independent selection of electrode area, interelectrode spacing, and frequency response or bandwidth. A detailed performance modeling program was written to predict the performance of various TLFC configurations. This program was used to design the first development model TLFC (designated UHSFC-2) for the Clinch River Breeder Reactor Project as a backup to the ex-vessel, BF_3 source-range flux monitors. Its operating temperature was only 180°C, so most of the internal structure was fabricated from aluminum to minimize extraneous neutron absorption.

DESIGN AND FABRICATION

The HTHSFC was designed and fabricated to meet LMR requirements for high neutron detection efficiency and high temperature operation. Major design criteria for the HTHSFC derived from our own experience, as well as experience gained from both foreign and domestic high temperature counter and cable irradiation programs. These criteria are as follows:

(1) All metal parts of the counter are to be fabricated from Inconel-600, which retains its strength at temperatures beyond 1000°C and appears to be relatively resistant to nitriding. In particular, the use of titanium[2] and nickel[5] is to be avoided if possible because of poor irradiation performance.

(2) Electrodes are to be designed to minimize thermally induced strains. Cylinders are to be prime candidates because of their low susceptibility to thermally induced strains and warpage.

(3) No brazes or solders are to be used in the counter. All connections, both electrical and mechanical, are to be made by TIG welding, spot welding, or pinning.

(4) Rotation of all internal parts due to thermal ratcheting is to be mechanically restrained to reduce the probability for stress related breakage of internal electrical connections.[5]

(5) Integral coaxial signal cables are to have copper inner and outer conductors separated by magnesia dielectric to provide a low loss signal transmission path (~0.07 dB/m) between the counter and its preamplifiers.[12]

(6) Internal electrical insulators and cable hot end seals[12] are to be fabricated from high purity alumina for improved resistance to neutron damage.

The HTHSFC design minimizes compressive and tensile loads between mating parts while maintaining a uniform spacing between anodes and cathodes during thermal cycles. The electrode assembly is supported by four rods on one end of the containment vessel to allow relative motion with respect to the vessel wall (Fig. 1). Anode and cathode cylinders were straightened to within 76 μm to minimize effects of strains resulting from residual stress at the 600°C operating temperature.

Many custom parts were used in the fabrication of the HTHSFC. Westinghouse Hanford Engineering Development Laboratory (HEDL) fabricated the 33-Ω characteristic impedance, high temperature, Inconel sheathed integral MgO-dielectric cable assemblies according to ORNL specifications. The tubular anodes and cathodes were fabricated at ORNL and then shipped to Reuter-Stokes, Inc., for deposition of the $^{235}UO_2$ coatings. The alumina insulators were precision machined by McDanel Refractory Company.

During assembly, the HEDL cables and two fill tubes were welded to the Inconel header plate of the detector. To assure good electrical contact and

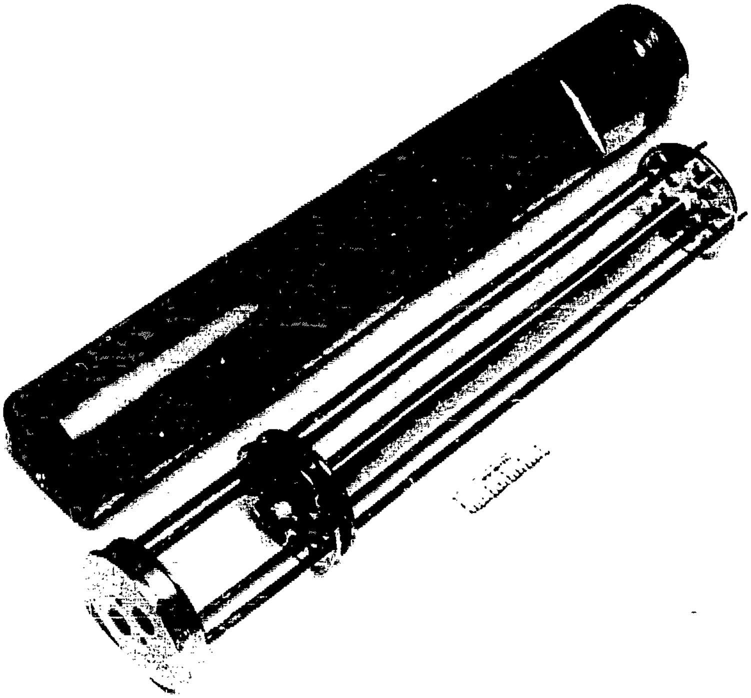

Fig. 1. The electrode assembly of the HTHSFC is a self-contained structure built on a framework of insulator support plates and four spacer rods. The assembly is mechanically fixed to the envelope only by the header flange weld to permit differential thermal expansion.

mechanical support, the 19 Inconel cathode tubes were welded to the upper insulator support plate. Precision alumina insulators at each end of an electrode pair maintain an annular electrode gap of 1.5 mm. The last step in assembly of the electrode structure was to interconnect the anodes serially with inductors wound from Inconel wire (Fig. 2). Length, diameter, and pitch of these inductors were adjusted to provide a lumped-element transmission line having a characteristic impedance of 33 Ω in conjunction with the interelectrode capacitance of one anode-cathode pair. All electrical connections between anodes, inductors, and cable center conductors were made by spot welding. The Inconel envelope of the counter (11.5 cm OD by 76 cm long) was designed to withstand at least 6×10^5 Pa of pressure at 600°C. Welding of this envelope to the header flange completed assembly.

The resulting HTHSFC utilizes a TLFC electrode configuration consisting of 19 sets of coaxial cylinders coated with 1.5 mg/cm^2 of 97% enriched $^{235}UO_2$ (also containing 0.7% ^{234}U with the balance ^{238}U). These cylinders have a total coated electrode area of 0.75 m^2. Thus, total uranium inventory is 9.9 g and the neutron detection sensitivity is estimated to be ~6 to 7 cps/nv_{th}.

In general, we adhered closely to the six previously stated design criteria, with the only exception being the use of fully annealed nickel for the gas-fill tubes. This exception was made to provide relatively ductile tubes which can easily be pinched off from a vacuum manifold with a cold-welding tool after addition of fill gas.

Fig. 2. This end view of the HTHSFC electrode assembly shows Inconel inductors welded to the anode stubs to form a lumped-element, LC delay line. . otation of alumina insulators is prevented by interlocking hexagonal flats which can be seen between insulator support plates.

Because the cable hot end seals were outgassed at 650°C, the processing temperature for the counter-cable combination was limited to <650°C. We plan to outgas the counter at 625°C to provide an adequate safety margin for 600°C operation. To obtain preliminary data for this paper, we interrupted the outgassing procedure at 200°C and backfilled the counter with a mixture of 90% Ar + 10% N_2 to a pressure of 2.03×10^5 Pa absolute. The same composition and pressure will be used for the final backfill.

Nitrogen is the only gas additive that has performed satisfactorily during high temperature irradiation experiments. At an operating voltage in the 500- to 700-V range, the 10% mixture provides electron drift velocities of 4 to 5 cm/μs and electron collection times of 30 to 40 ns.

INSTRUMENTATION

The scope of electronic circuitry discussed in this paper will be limited to components required for initial testing of the HTHSFC. These electronics include two preamplifiers, two pulse-shaping amplifiers, an amplitude discriminator with coincidence capabilities, and a three-channel timer-scaler.

A Hewlett Packard Model 8447A dual amplifier was selected as the preamplifier because of its high gain (10X/stage), large bandwidth (400 Mhz), and low input noise (~20pA/$\sqrt{\text{Hz}}$). Each signal cable was connected to a series combination of two preamplifier stages for a total gain of 100. For expediency, an impedance mismatch of 33 to 50 Ω between the signal cables and the input of the preamplifiers was accepted during preliminary data acquisition. Impedancematching transformers will be used to properly match impedances for improved signal-to-noise ratios in future systems. Alternatively, ORNL-developed shunt feedback preamplifiers could be used to directly match the 33-Ω cable impedance.[13]

Each shaping amplifier was built from the circuit board of a commercial timing amplifier (ORTEC Model 574) that contains four independent, direct coupled amplifier stages having a gain of 4.5 and a bandwidth of 300 MHz in a 50-Ω system. The four amplifier stages on each board were employed as interstage amplifiers for a three-section, passive filter of near-optimum signal-to-noise ratio.[14] The transfer characteristic of this filter produces a unipolar, near-Gaussian shaped pulse of ~50 ns duration in response to a current impulse at the input. As shown in Fig. 3, the shaping amplifier outputs drive leading-edge (LE) discriminators, which drive either a time interval analyzer for measurements requiring spatial sensitivity or a bilateral coincidence gate for integral counting.

PERFORMANCE CHARACTERISTICS

The HTHSFC can be used to perform integral counting in either of two modes. In noncoincidence mode, output pulses from either LE discriminator are counted. In coincidence mode, output pulses from the bilateral coincidence gate are counted. The latter type of data is plotted in Fig. 4 as integral pulse height distributions (i.e., plots of positive threshold-level crossing rates versus threshold level). The advantage of the coincidence mode lies in the ability to operate at effectively higher threshold settings for greater immunity to random noise (i.e., preamplifier noise, inherent alpha pileup noise, and gamma pileup noise if present) without an attendant loss in neutron sensitivity. Based on a 50-ns pulse duration, the rate capability of the HTHSFC is 2 MHz with <10% counting losses. Counting losses should also be less than 10% for operation in gamma fields up to 2×10^5 R/h.

A pulse height spectrum of the time interval analyzer output (Fig 5.) shows individual neutron responses at each of the TLFC's 19 nodes. The shape of the peak height envelope responds to changes in the position of the neutron source. Similar time spectra can be obtained from the counter's response to inherent alpha activity, but lower signal-to-noise ratios do not provide complete resolution of the individual peaks. Nevertheless, a characteristic time signature is obtained which permits in situ verification of operability at zero neutron flux.

DISCUSSION

Because the HTHSFC has not been outgassed at the 625°C processing temperature, it is a bit premature to claim that we have met our primary goal of developing a 600°C fission counter for LMR applications. This claim will have to wait until successful completion of irradiation testing at the Experimental Breeder (EBR-II) in Idaho. However, preliminary test data indicate that a number of secondary goals have already been accomplished. Among these are the following:

(1) Measurement of the neutron integral pulse height distribution shows that the counting plateau is reasonably flat. Thus, neutron detection sensitivity can confidently be estimated at >5 cps/nv_{th} based on the total ^{235}U inventory.

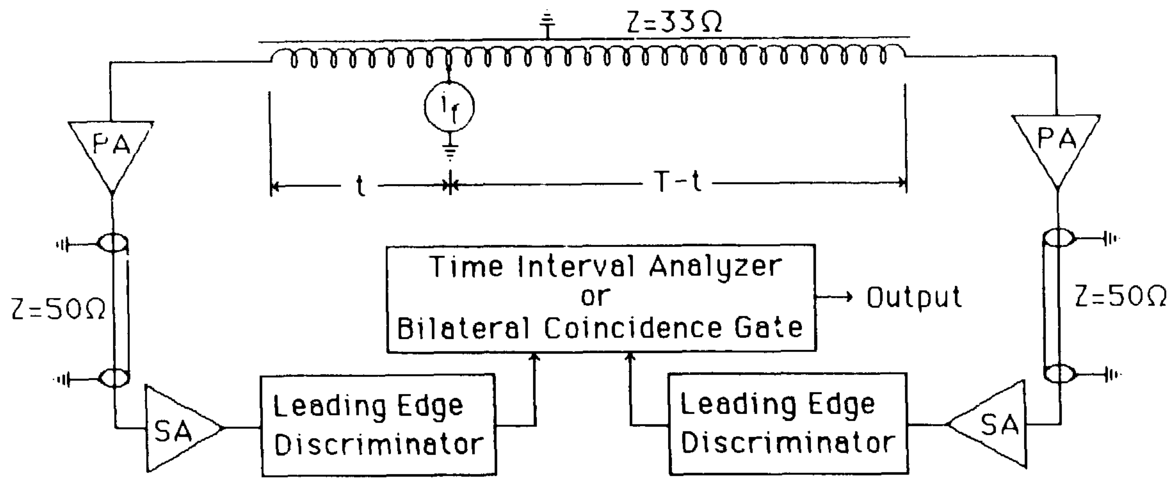

Fig. 3. A TLFC has two signal outputs, each of which is instrumented with a preamplifier (PA), a shaping amplifier (SA), and a leading edge (LE) discriminator. The position of a fission pulse (i_f) is decoded from the time difference between discriminator outputs by a time interval analyzer. Output of the bilateral coincidence gate (resolving time ~1.1T where T is the total pulse transit time) is used for integral pulse counting and provides improved rejection of spurious pulses from uncorrelated noise sources.

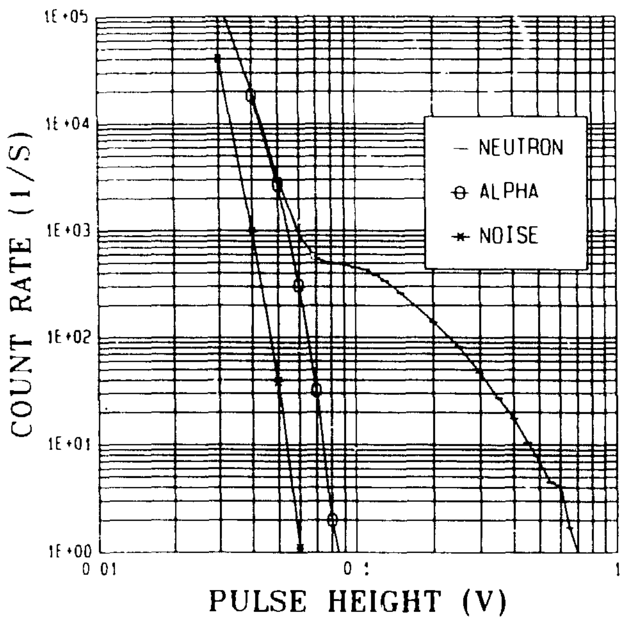

Fig. 4. Integral pulse height spectra for the HTHSFC show excellent noise and alpha-pileup suppression of coincidence mode counting which permit use of low operating points (~0.09 V) to maximize effective neutron sensitivity.

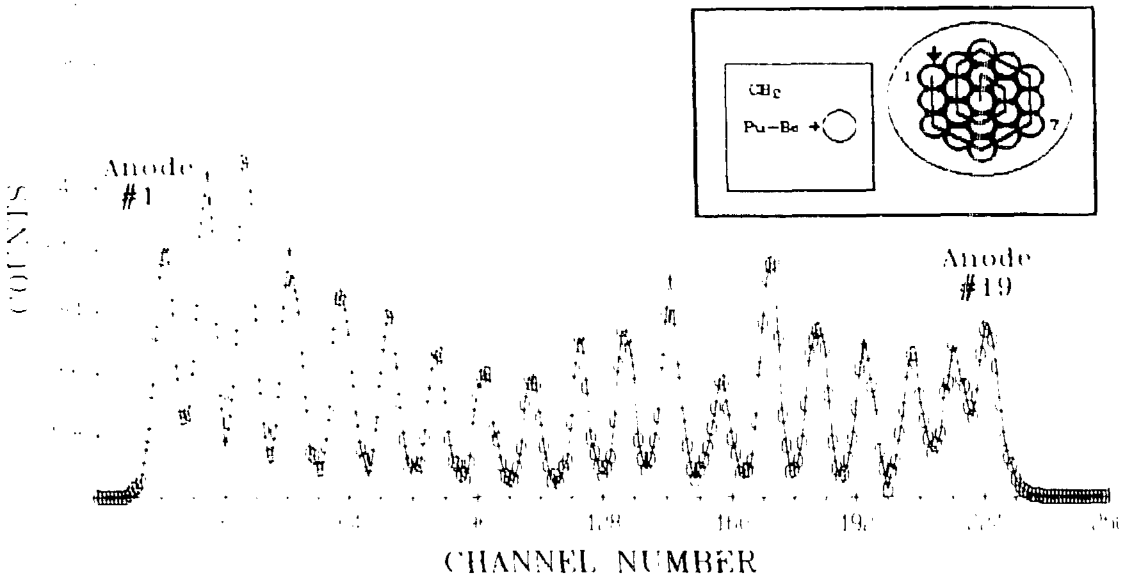

Fig. 5. A characteristic time spectrum of the HTHSFC demonstrates position sensitivity of the counter to a moderated neutron source located as shown in the inset diagram. The conversion gain is 0.77 ns/channel. Low response of the 13th node in the TLFC may be due to a below-average coating thickness.

(2) The data provide verification for the computer modeling prediction that use of relatively resistive Inconel wire for the coupling inductors will not seriously degrade the transfer function of the TLFC. Also, the data verify the prediction that use of constant-k filter sections in the lumped transmission line (rather than m-derived sections as in the UHSFC-2) will not seriously degrade the transfer function of the TLFC.[15]

(3) Measured time spectra indicate that the HTHSFC is sensitive to radial neutron flux gradients and therefore can provide information concerning azimuthal position of the neutron source. This feature could prove useful in LMR applications for distinguishing response to core neutrons from response to in-vessel stored fuel.

Our greatest uncertainty concerning the survivability of the HTHSFC under high temperature irradiation conditions is the stability of the $Ar\text{-}N_2$ fill-gas mixture. We are currently irradiating a high temperature test counter (designated FC3HT-2) at EBR-II, which is still operable after an exposure of $\sim 1.5 \times 10^{18}$ neutrons/cm^2 (nvt) at 550°C. Previously, an identical detector (FC3HT) survived a year of preirradiation testing at 550°C with no measurable changes in performance. Both detectors were fabricated from type 304 stainless steel and backfilled with a mixture of 90% Ar + 10% N_2. We believe the gas mixture will be at least as stable in an Inconel environment (i.e., the HTHSFC) as it has been in our stainless steel counters.

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